

Dietrich Fengel, Gerd Wegener · Wood

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Wood

Chemistry, Ultrastructure, Reactions

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Preface

One of the most important characteristics of wood is its renewability. It may even be inexhaustible providing that it is used with foresight and long-range planning. In an age of dwindling fossil-fuel resources, alternative resources such as wood which are continuously regenerated by nature become all-important.

To use wood wisely and judiciously we need to have a basic knowledge of its composition and structure as well as its behaviour under various external influences. Chemical studies of wood and its components may provide decisive factors not only for its applicability but also for the economic feasibility of many processes involving wood.

In the past several excellent books were published summarizing our knowledge of wood chemistry. Those by Hägglund, Wise and Jahn, Nikitin, Sandermann, Browning, and Kürschner deserve special mention. The latter two volumes appeared in 1963 and 1966, respectively. More recently a concise survey of wood chemistry was presented by Sjöström (1981). Progress in specific fields is described in various monographs such as 'Lignins' by Sarkanen and Ludwig (1971), 'Cellulose and Cellulose Derivatives' by Bikales and Segal (1971), and 'Pulp and Paper' by Casey (1980).

The aim of this book is to present a comprehensive account of progress and current knowledge in wood chemistry, drawing on the specialist literature from 1960 to 1982. For earlier publications the reader is generally referred to summarizing articles and books.

This volume falls implicitly, if not explicitly, into three large sections with a fluent transition between them. The first section describes the fundamentals of wood structure, analysis and components. Owing to the increasing interest being shown in bark, the structure and chemistry of this wood-joint product is summarized in a separate chapter. In the second section the reader will find reactions of wood and its components under degrading and changing conditions. The last section deals with the utilization of wood and wood components isolated by various chemical processes.

Since each component of wood has not only a chemical formula but also a molecular and supramolecular structure, and since most wood components are closely associated within the cell wall, the chemical compounds and reactions are also regarded from the standpoint of their ultrastructural aspects.

In order to visualize the structure of wood in diverse dimensions numerous scanning and transmission electron micrographs are presented in addition to light micrographs.

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A great number of our colleagues followed the writing of this book with interest. Many of them supported our work by providing illustrations, granting permission for publication or making suggestions regarding the literature. This is sincerely appreciated. We are also greatly indebted to Drs H. von Aufsess, D. Grosser and M. Stoll for reading parts of the manuscript and offering valuable comments. We further wish to express our gratitude to all the coworkers in our laboratory who contributed with great enthusiasm and commitment to the preparation of the manuscript, above all Miss S. Hess. Thanks are also due to Mr J. B. Robinson for his conscientious revisions of the English. Last but not least we would like to thank the publishers for the attractive presentation of our book.

Munich, November 1983

Dietrich Fengel
Gerd Wegener

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1. Introduction

Wood is a very old raw material. Thousands of years ago, when giant forest covered large areas of the earth's surface, primitive man used wood for fuel and tools. Because wood is natural in origin, serving to strengthen stems, branches and roots of trees and other plants, it returns to the natural cycle after having done its task, and is degraded into its basic elements. This explains why so little evidence of the early utilization of wood has survived, though some arrowheads, spears and tools up to 300 000 years old have been preserved under exceptional conditions in swamps and marshland.

During the prehistoric and historic periods wood was not only used as a building material but also increasingly gained importance as a chemical raw material for the production of charcoal (used in iron smelting), tar and pitch (useful for preserving and sealing ship hulls), and potash (used in glass production and as a bleaching agent for linen and cotton textiles).

But in another sense wood is a very modern raw material. Broad timber vaultings and precious furniture attest to its usefulness and beauty. Even in converted forms such as plywood, particleboard and fibreboard, wood has become a valuable building material. And, last but not least, wood is the basic substance for pulp and paper, fibres, films, additives, and many other products.

It is no exaggeration to say that wood is one of the most important products of nature. About one-third of the world's land surface is covered by forests containing a total growing stock of some 300 000 million m³ of wood (Steinlin 1979). From this stock 2 600 million m³ are harvested each year. This volume represents about 1 300 million tons of wood, an amount approximately equal to the world's production of corn ($1\,500 \cdot 10^6$ t), twice the production of steel ($700 \cdot 10^6$ t) or cement ($760 \cdot 10^6$ t), and 27 times the production of plastics ($48 \cdot 10^6$ t) (Statistisches Bundesamt 1981).

During the present century the world's consumption of wood increased considerably, and forecasts for the period up to the year 2000 predict a further rapid increase (FAO 1966, 1974, 1981; Hagemeyer 1976; Stone, Saeman 1977; Steinlin 1979). The estimates of the world's total requirements of roundwood in the year 2000 vary between 3 800 and 6 200 million m³. Prognostications show that demand for industrial roundwood will nearly double, that for pulpwood nearly triple during the final 20 years of this century (Fig. 1–1). The relatively large amount of wood used for fuel (1 500 million m³ in 1979) is expected to increase only slightly during this period.

These figures are offset by an estimated annual growth increment of 7 000 to 9 000 million m³ (FAO 1966; Steinlin 1979). The annual growth of wood varies greatly

2 Introduction

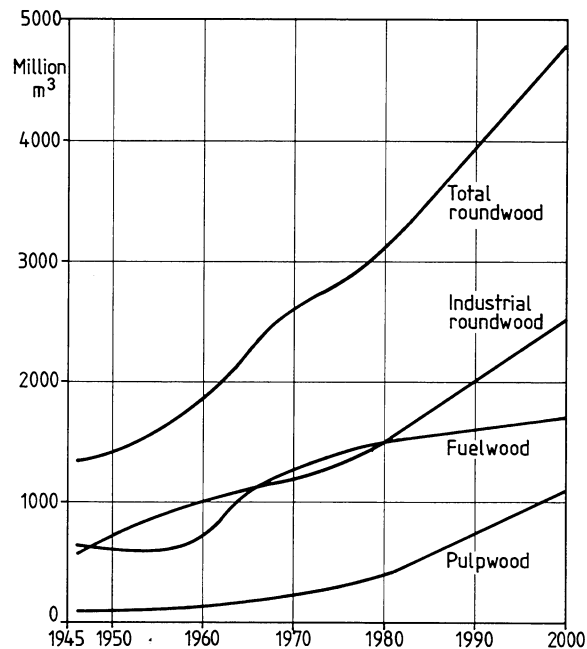


Fig. 1-1. World's consumption and requirements of wood 1946-2000 (according to FAO 1966, 1981; Hagemeyer 1976; Stone, Saeman 1977; Steinlin 1979).

according to climate and soil conditions. Whereas in temperate zones the increment is about 3 to 5 m³ per hectare and year, tropical eucalyptus and pine plantations may produce 15 to 20 m³ per hectare and year. Since world forest inventories also include forest-like vegetation, the mean increment in wood all over the world is no more than 1 to 2 m³ per hectare and year (FAO 1966).

Sanderman (1973) has calculated that under optimal conditions a fast-growing pine may produce 13.7 g of cellulose per day. This quantity of cellulose corresponds to 8.2 g lignin, 6.5 g polyoses, and 0.3 g extractives, which results in a total of 27.7 g or about 56 cm³ of wood substance being produced by one tree per day.

Nevertheless, a progressive reduction of the growing stock towards a value of about 23% of the earth's land surface in the year 2000 is predicted. This represents a decrease of 31%, with an above-average decrease of about 40% in the developing countries (Barney 1980). The situation is expected to stabilize in the year 2020, by which time all accessible forests in the developing countries will have been removed. This problem is closely connected with fuel consumption, which is predominantly based on wood and agricultural waste in these countries (Table 1-1). In some countries, non-commercial fuels constitute more than 90% of the total (Leach 1979). A restriction of the consumption of fuelwood is becoming more and more difficult with increasing prices for the commercial petroleum-based fuels.

Table 1-1: Fuel consumption in various world areas (in million tons coal equivalent) (Leach 1979)

Region	Commercial fuels	Fuel wood	Agricultural waste	Total	Fuel wood + agricultural waste as % of total
Africa*	66	116	22	204	68
Mideast	109	5	12	126	13
Far East**	247	143	100	490	50
Latin America	304	98	31	433	30
West Europe	1 568	18	6	1 592	2
USSR and Eastern Europe	1 771	43	24	1 838	4
North America	2 723	7	0	2 730	0
World***	7 885	498	167	8 550	8

* Excluding South Africa

** Excluding Japan

*** Including Japan, South Africa, Australia, etc.

The most important product of the chemical conversion of wood is pulp. All over the world 123 million tons of pulp were produced in 1980 (Fig. 1-2). During the same period the total consumption of paper and paperboard was 171 million tons, of which more than 25% were produced from wastepaper (VDP 1981). In some countries (e.g. Japan, Great Britain, F. R. Germany, G.D.R., Italy) wastepaper application exceeds 40–50%. This indicates that recycling is an important factor in the economic utilization of the raw material. Economic and environmental problems are reasons for a progressive change of pulping and bleaching processes.

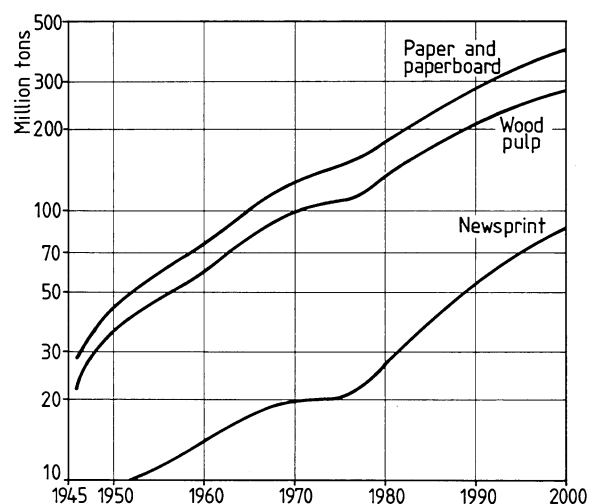


Fig. 1-2. World's production of wood pulp, paper and paperboard, and newsprint 1946–2000 (according to FAO 1966; Keays 1975; VDP 1981).

4 Introduction

Table 1-2: Consumption of paper and paperboard in some countries and regions (kg/head) (VDP 1967, 1981; Hagemeyer 1976)

	1966	1979	1985	2000
U.S.A.	240	289	} 349	566
Canada	141	215		
Japan	50	151	284	558
U.S.S.R.	21	33	67	192
Western Europe				
E.G.	81	128	} 180	324
E.F.T.A.	105	135		
Other countries*		6	17	23
World	31	40	55	91

* Stands for the bulk of the developing countries

A survey of the development of paper and paperboard consumption shows that, despite high consumption in the highly industrialized countries, an increase of consumption is still possible (Keays 1975) (Table 1-2). On the other hand the consumption of paper in the developing countries is so low that a drastic increase seems to be unavoidable, certainly in the long run. We can expect the level of consumption in most developing countries to approach that of the industrial nations sometime well after the year 2000, particularly if the forecast is true that even in 2000 a one-dollar increase in the gross national product of the developing countries will be met by a 20-dollar increase in the industrial countries (Barney 1980).

In view of the future it is our task and duty to utilize wood economically so that it remains a significant resource. A knowledge of wood components and their chemical behaviour is more important now than ever. There is a need for effective protection against external influences (chemicals, enzymes, irradiation, temperature) on the one hand, and on the other for a careful isolation of wood components, and a search for new products based on them. For a better understanding of known technologies and further development of new processes, basic research into the isolation, characterization and reactions of wood components is still essential.

The chemistry of wood and its components cannot be regarded apart from its structure. Wood is not merely a chemical substance, or an anatomical tissue, or a material – it is a combination of all three. This entirely results from an intimate association of the chemical components which form ultrastructural elements, being combined into higher-order systems which in turn build up the walls of the cells that ultimately compose the wood tissue.

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2. Structure and Ultrastructure

2.1. Anatomical Aspects

Before reflecting on the microscopic and submicroscopic structure of wood a short survey of the anatomical features of softwoods and hardwoods is advisable. For more detailed information the reader is referred to the specialist literature: Wagenführ (1966), Jane (1970), Panshin and de Zeeuw (1970), Bosshard (1974), Wagenführ and Scheiber (1974), Grosser (1977), Schweingruber (1978), Sakai (1982). From the anatomical point of view wood is a perennial tissue resulting from the secondary growth in the stems, branches and roots of trees and shrubs.

The observation of wood without optical aids shows not only differences between softwoods and hardwoods as well as between various species, but also differences within one sample, such as sapwood and heartwood, growth rings, earlywood and latewood, the arrangement of pores etc. All these phenomena are the result of the development and growth of wood tissue. This tissue is constructed to meet the natural necessities of the tree, and consists therefore of strengthening, conducting and storing cells. Softwood obtained from coniferous trees and hardwood obtained from deciduous trees differ in cell type and cell function (Table 2-1).

The run and the arrangement of the cells can be recognized on the sections cut in the three main planes used for the anatomical characterization of wood: the cross or transverse section, the tangential section and the radial section (Fig. 2-1).

Softwood shows a relatively simple structure as it consists of 90–95% tracheids, which are long and slender cells with flattened or tapered closed edges (Fig. 2-2a). The tracheids are arranged in radial files, and their longitudinal extension is oriented in the direction of the stem axes (Fig. 2-3).

Table 2-1: Main functions of the various cell types in wood

	Mechanical function	Conducting function	Storing function	Secreting function
Softwoods	Latewood tracheids	Earlywood tracheids Ray tracheids	Ray parenchyma Longitudinal parenchyma (Resin canals)	Epithelial cells
Hardwoods	Libriform fibres Fibre tracheids	Vessels Vessel tracheids	Ray parenchyma Longitudinal parenchyma (Resin canals)	Epithelial cells

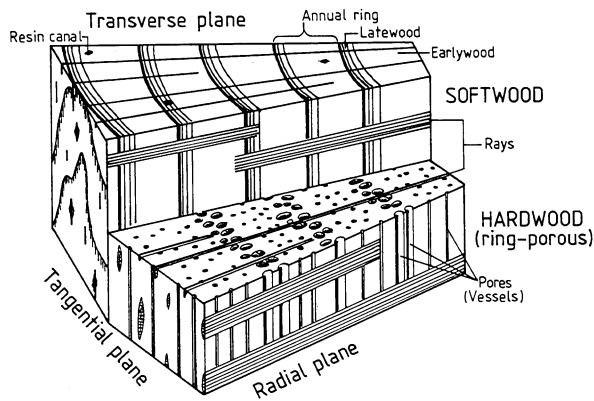


Fig. 2-1. Models of a softwood and a hardwood block, showing the main cutting planes for anatomical studies, and anatomical structures visible without optical aids.

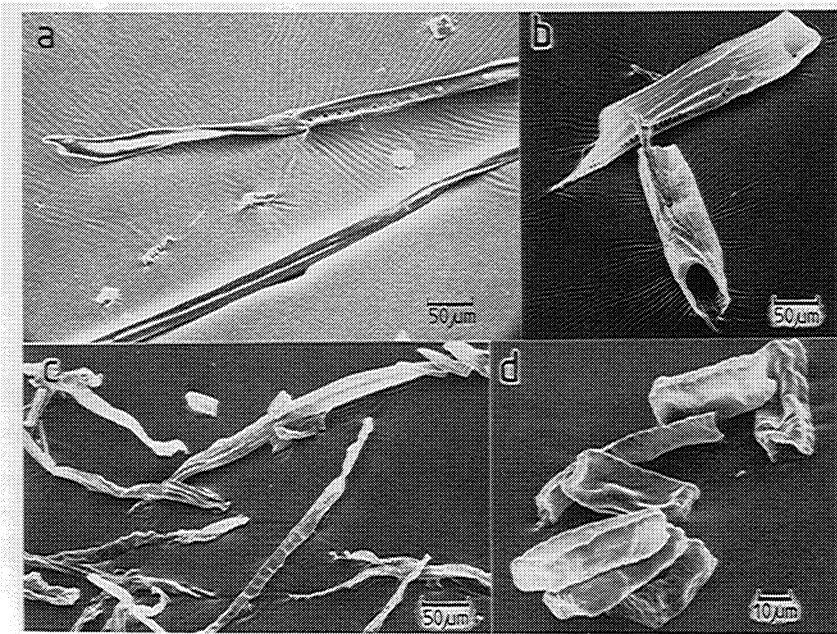


Fig. 2-2. Cells and cellular elements of softwoods and hardwoods. SEM micrographs, all at the same level of magnification, except for d).

- a) Softwood tracheids (*Pinus sylvestris*);
- b) Hardwood vessel elements (*Fagus sylvatica*);
- c) Hardwood fibres (*Quercus robur*);
- d) Hardwood parenchyma cells (*Quercus robur*).

In evolving from earlywood to latewood the cell diameters become smaller while the cell walls become thicker. At the end of the growth period tracheids with small lumina and small radial diameters are developed, while at the beginning of the

subsequent growth period tracheids with large lumina and diameters are developed by the tree (Fig. 2–4). In spruce (*Picea abies*) minimal radial diameters of about 7 μm for the last latewood tracheids and maximal radial diameters of 32 μm for the first earlywood tracheids were determined (Fengel, Stoll 1973). This abrupt change is visible to the eye as an annual or growth ring.

The thick-walled latewood tracheids provide strength, while the spaceous earlywood tracheids predominantly conduct water and minerals within the tree. Various softwoods, such as larch (*Larix* spp.), spruce (*Picea* spp.), pine (*Pinus* spp.) and Douglas fir (*Pseudotsuga menziesii*), also contain radially oriented tracheids accompanying the ray parenchyma cells.

The storage and the transport of assimilates take place within the parenchyma cells, which in softwoods are predominantly arranged in radially running rays

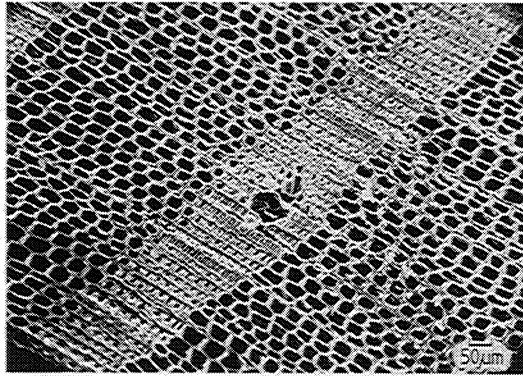


Fig. 2–3. Transverse plane of a softwood (*Pinus sylvestris*) with a whole annual ring, showing the transition between earlywood and latewood within the annual ring and at the ring border. In the latewood centre is a resin canal. SEM micrograph.

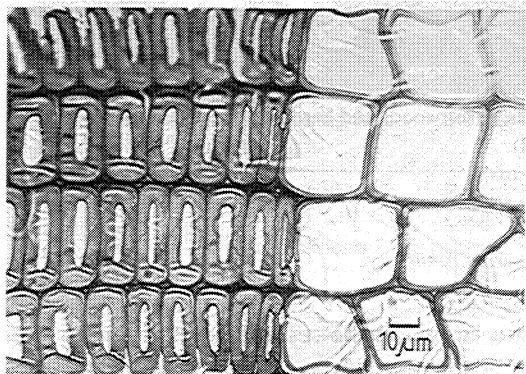


Fig. 2–4. Cross section of the annual ring border in a softwood (*Picea abies*). Light micrograph.